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Intercontinental Time and Frequency Transfer Using a Global Positioning System Timing Receiver

P. A. Clements
Communications Systems Research Section

The DSN has a requirement to maintain knowledge of the frequency offset between DSN stations with 3×10^{-13} and time offset within 10 microseconds. It is further anticipated that in the 1987-1990 era the requirement for knowledge of time offset between DSN stations will be less than 10 nanoseconds.

JPL is using the Global Positioning System (GPS) Space Vehicles, as a development project, to transfer time and frequency over intercontinental distances between stations of the DSN and between the DSN and other agencies. JPL has installed GPS ng receivers at its tracking station near Barstow, California, and at its tracking st near Madrid, Spain.

The details of the experiment and the data are reported. There is a discussion of the ultimate capabilities of these techniques for meeting the functional requirements of the DSN.

I. Introduction

The DSN has a requirement to maintain knowledge of frequency offset between complexes of 3×10^{-13} ($\Delta f/f$), and a knowledge of time offset to within 10 microseconds. It is further anticipated that in the 1987-1990 era the requirement for knowledge of time offset between DSN complexes will be less than 10 nanoseconds (ns). Clearly, new measurement techniques will be needed to meet these requirements.

Among the new measurement techniques being investigated by JPL, to meet these requirements, is the use of Global Positioning System (GPS) timing receivers. The GPS timing receivers presently being used by JPL were developed and built by the National Bureau of Standards (NBS). Part of this development was funded by JPL.

II. Description of the Receivers

The NBS receiver is described in the 1982 proceedings of the Precise Time and Time Interval Applications and Planning Meeting (Ref. 1). It uses one frequency containing the CA code which is transmitted by each space vehicle. The receiver locks on the space vehicle's signal; therefore, it needs only a small omnidirectional antenna rather than a steerable dish. The receiver is controlled by an internal microprocessor that automatically handles schedules, length of reception time, and other tasks. Once the receiver is set up, normal operation only

requires occasional human intervention. For instance, the reception time is decremented 4 minutes every day which of course is a little different than a sidereal day. This is done to make it a bit more convenient by having to deal only with whole minutes. It is necessary to adjust the schedule every few weeks to keep the viewing angles correct.

III. Configuration of the System

At present JPL has two GPS timing receivers, one of which is located at the Goldstone Tracking Station Complex (GTS) near Barstow, California. This receiver gets its 1-second timing pulse from a cesium clock, Goldstone clock 5, GTS(C15), which is located about 20 km from a hydrogen maser clock Goldstone Station Reference GTS(SR), which is at another station (DSS 14) in the same complex. The hydrogen maser clock is the same one used in Very Long Baseline Interferometry (VLBI) which measures, among other things, the time offset between the DSN complexes. A clock trip using a portable cesium clock is made once a week between GTS(C15) and GTS(SR). These clock trips are done in conjunction with the regularly scheduled weekly VLBI measurements.

The second GPS timing receiver is located at DSS 61/63. The Madrid receiver gets its timing pulse from a hydrogen maser clock which is that station's reference clock MAD(SR). MAD(SR) is another hydrogen maser clock used in the VLBI measurements and is at the other end of the weekly VLBI measurement between California and Spain.

Two other receivers involved in this test were located at NBS in Boulder, Colorado, and at the United States Naval Observatory (USNO) in Washington, DC. The NBS receiver is identical to those used at JPL. It gets its timing pulse from the NBS clock 9 which is one of the clocks in the NBS ensemble. A daily offset of clock 9 to UTC(NBS) is available at the month's end and the receiver is accessible by telephone through a modem. The USNO GPS timing receiver is a Stanford Telecommunications receiver of similar functional design to the NBS receiver. Its schedule is decremented 4 minutes per day[1]. The receiver gets its timing pulse from UTC(USNO, MC). There are corrections available to UTC(USNO).

IV. Procedures for Gathering and Processing the Data

The receivers will store internally one to two weeks of data depending on how much data is acquired during each day. The data from the receivers are acquired by telephone usually once a week. In the use of the NBS type receiver, the receivers themselves are accessed. In the case of the USNO receiver, the data are acquired from a public database service provided by USNO. In both cases the data are transmitted at a 300-baud rate and are received and printed out on a terminal. The data are then entered by hand into a Hewlett Packard 9845 calculator at JPL.

All of the data were taken during a mutual view of the GPS space vehicle by pairs of timing receivers. This method promises the best results and is the simplest with respect to processing the data. As more space vehicles are added to the GPS constellation, there will be additional opportunities for mutual view around the world.

The receivers are programmed to take data for 10 minutes (600 seconds). These data are then reduced in the receiver to a single data point which represents the time offset between the local clock and the GPS clock. The difference between the two values of local clock and GPS time is then calculated. This is done for each space vehicle that is available for mutual view each day. These values are then averaged to produce a single value for the day. If data points are missing, then a linear interpolation is made on the original measurement.

V. Results

The first measurement in late 1982 was clock 5 at GTS and NBS clock 9. The distance between these two stations is approximately 1200 km and regular clock trips were made between GTS and NBS so the measurements could be verified. The data axis of all of the figures is labeled in Modified Julian Day (MJD). An MJD of 5225 represents September 13, 1982, on the conventional calendar.

Figure 1 shows the results of the UTC(NBS) - GTS (clock 5) with the results of the cesium portable clock trips shown. Because of different antennas being used at NBS a receiver calibration was not available; therefore the first clock trip was used as a calibration. The second trip disagreed by 36 ns and the third by 5 ns.

This receiver is now probably a de facto permanent installation at GTS and will probably eventually eliminate or at least curtail the need for most future clock trips between NBS and GTS.

A second GPS timing receiver was installed at the DSN station in Spain (DSS 63). A schedule of mutual observation (observed at the same time) of two space vehicles (SV5 and SV8) was started. These are the only two space vehicles that are mutually observable from both complexes. The space vehi-

[1]Prior to the first of 1983 and during the tests reported here, the USNO receiver schedule has been decremented 27 minutes one week and 28 minutes the alternate week. This allowed an approximation to a sidereal day. This was changed to a 4 min/day decrement starting about the first of 1983.

cle observation schedule was made to have the same angle of observation from both stations. Some slight adjustments were made to equalize the angles from 41 degrees to 45 degrees above the horizon. The space vehicles are over Greenland at observation time and seen within a few degrees of each other in the sky at each station.

A clock offset measurement is made every day from each space vehicle and the mean is used as the value of the clock offset. The same procedure for getting a value of clock offset is used between GTS(C15) and MAD(SR) and between UTC(NBS) and GTS(C15) with the exception that only two space vehicles are available between GTS and MAD. A plot of the clock offset values is seen in Fig. 2. Figure 3 is the same graph with a frequency offset removed.

The frequency offset between the GTS(C15) and MAD(SR) was calculated using 10 days of data. The calculations assumed statistical independence between the measurements using the two space vehicles. A typical frequency offset measurement was 9.5×10^{-13} ($\Delta f/f$) with a (confidence) standard deviation of the mean of 2.8×10^{-14} ($\Delta f/f$). This is within the requirements to have knowledge of frequency offset to within the 3×10^{-13} ($\Delta f/f$) DSN specification.

VI. Confirmation by Independent GPS Measurements

Unlike the clock offset measurements between GTS and NBS, the measurements from California to Spain cannot be confirmed by frequent clock trips. One attempt at confirmation was a daily indirect time difference measurement made through the U.S. Naval Observatory (USNO). This was accomplished in two steps: First, there was a daily mutual view schedule maintained by NBS, USNO and Goldstone. Second, USNO and Madrid maintain a mutual view schedule, which results in daily time offset measurement between their clocks. These direct and indirect time offset measurements between Goldstone and Madrid are nearly statistically independent.

Figure 4 shows the differences in the measurement of the time offset between Goldstone and Madrid by two different paths. There was a mean offset of 140 ns. An explanation of this could be an error in the coordinates of the receiver. There is some reason to believe this is true at Goldstone and there have been no checks made at Spain. The new firmware to be installed in 1983 into the NBS receivers will contain a navigation program. Then it will be possible to verify the antenna location within a few meters.

A good candidate for the cause of the daily variation is the different scheduling methods used by JPL and NBS and that used by USNO. This problem should clear up in data taken in 1983 after USNO started decrementing their schedule by 4 minutes/day. These tests have been continued during 1983 and will be reported in a future article. Some of the daily variations are probably caused by ionospheric changes. There is no attempt to account for this in the NBS and JPL receiver during this time but one would expect this error to be less than is presently seen.

VII. Confirmation Using VLBI Measurements

Approximately once every week a VLBI measurement is made between GTS and MAD and between GTS and the DSN Australian complex. One of the results of the VLBI measurement is the time offset between the involved stations. By using the regular clock trips between GTS(C15) and GST(SR), the GPS and timing receiver results can produce a weekly approximate time offset between GTS(SR) and the MAD(SR) (Fig. 5). These time offset measurements can be compared to the time offset results of the VLBI measurements as seen in Fig. 6.

A linear fit on each of the two sets of data shows an excellent agreement. These measurements will be continued throughout 1983. It is planned to make measurements internal to the stations to find the offset difference between the VLBI and the GPS measurements.

VIII. Conclusions

The conclusions of the experiment are as follows:

(1) The present GPS timing receivers can meet the 1985 requirements specified for the DSN. With better data collection, the addition of software filters in the data processing, and ionosphere correction, there is reason to believe the intercontinental time measurements, with the existing equipment, can approach an accuracy of 10–20 nanoseconds. Certainly, one can expect to further refine the measurement of frequency offset.

(2) The GPS and VLBI measurements of time offset will complement each other for some time to come.

(3) It has been shown that the GPS timing receiver is an operational item of equipment capable of replacing regular clock trips over short distances and shows promise of replacing clock trips over intercontinental distances.

Acknowledgments

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1. Unprecedented Syntonization and Synchronization Accuracy via Simultaneous Viewing with GPS Receivers; Construction Characteristics of an NBS/GPS Receiver, D. D. Davis, M. Weiss, A. Clements, D. W. Allan, 1981. *Proceedings of the 13th Annual Precise Time and Time Interval Applications and Planning Meeting*, Naval Research Laboratory, Washington, D.C.

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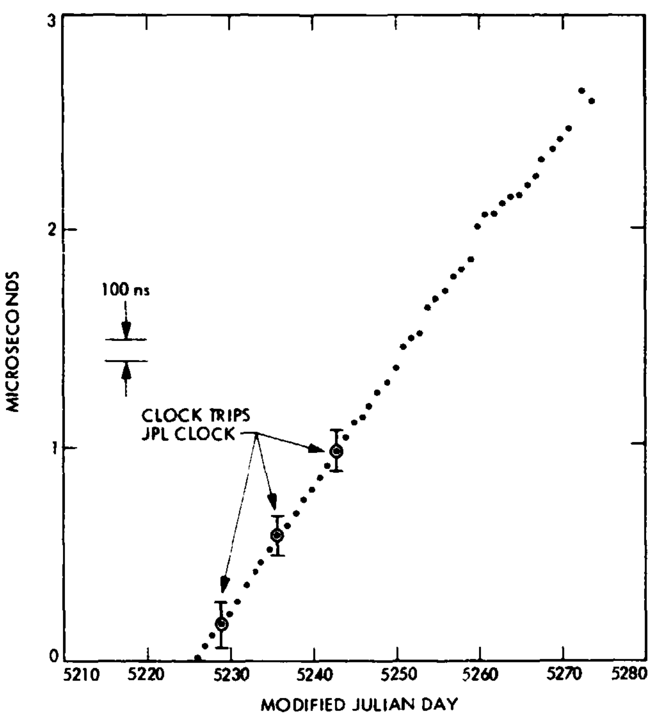

Fig. 1. UTC(NBS)–Goldstone (clock 5)

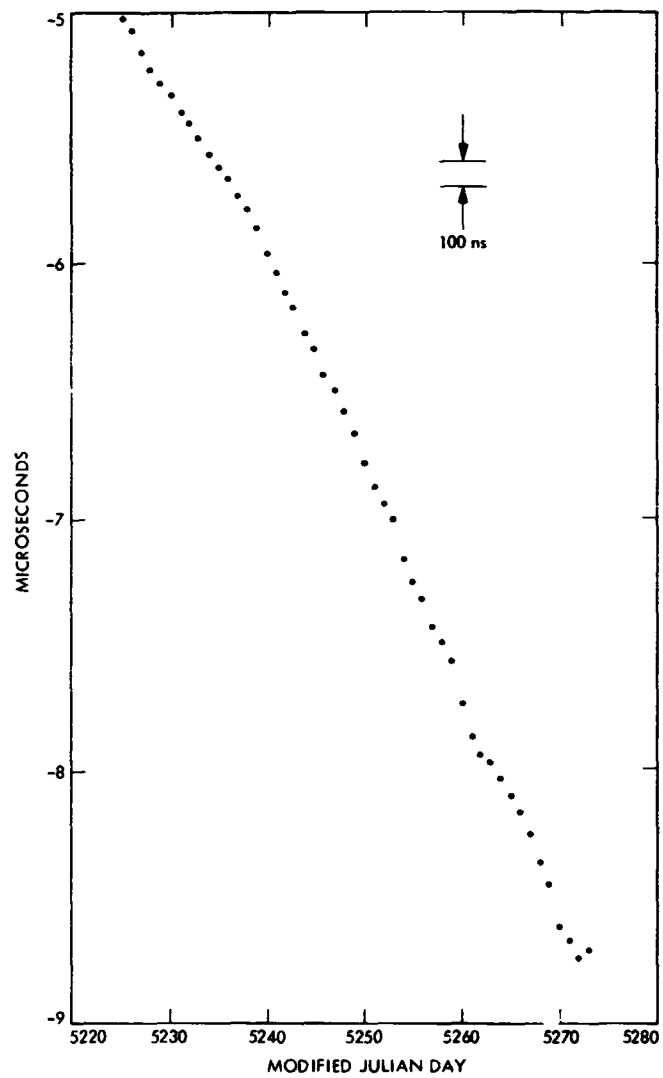

Fig. 2. Goldstone–Madrid as directly measured by GPS timing receivers (Goldstone [clock 5]–Madrid [station reference])

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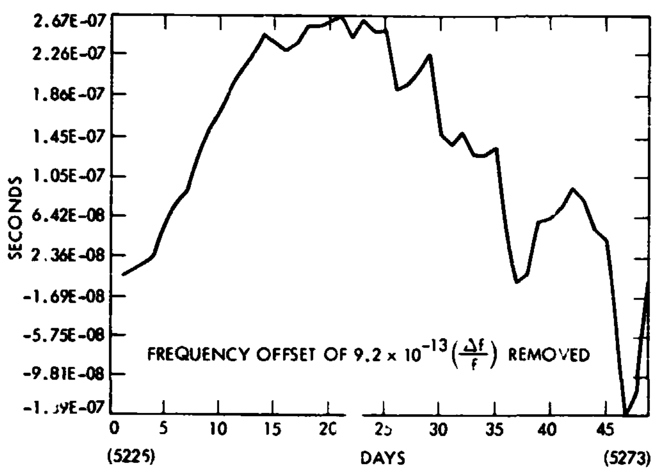

Fig. 3. Goldstone (clock 5)–Madrid (station reference)

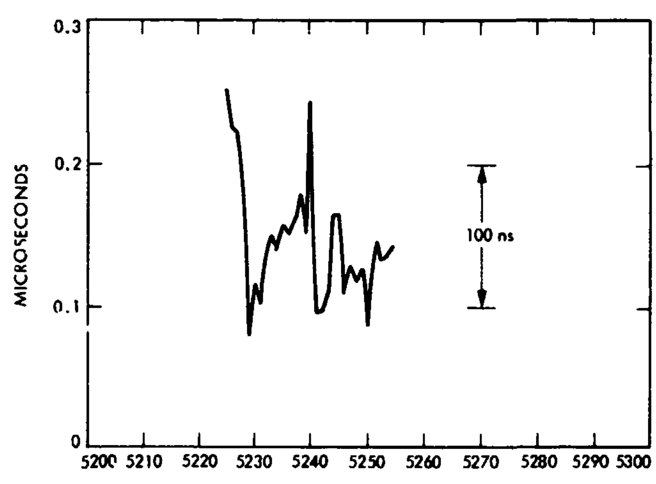

Fig. 4. Difference between Goldstone to Madrid time directly and through USNO

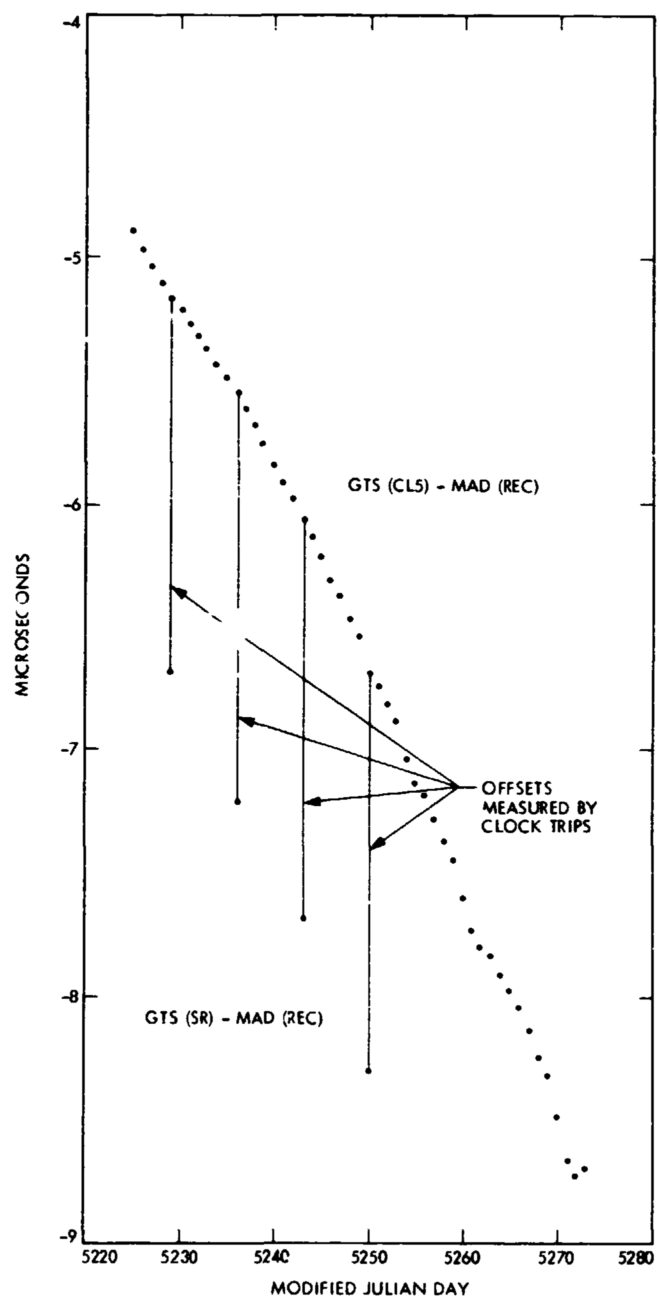

Fig. 5. Goldstone–Madrid directly showing offset to Goldstone (station reference)

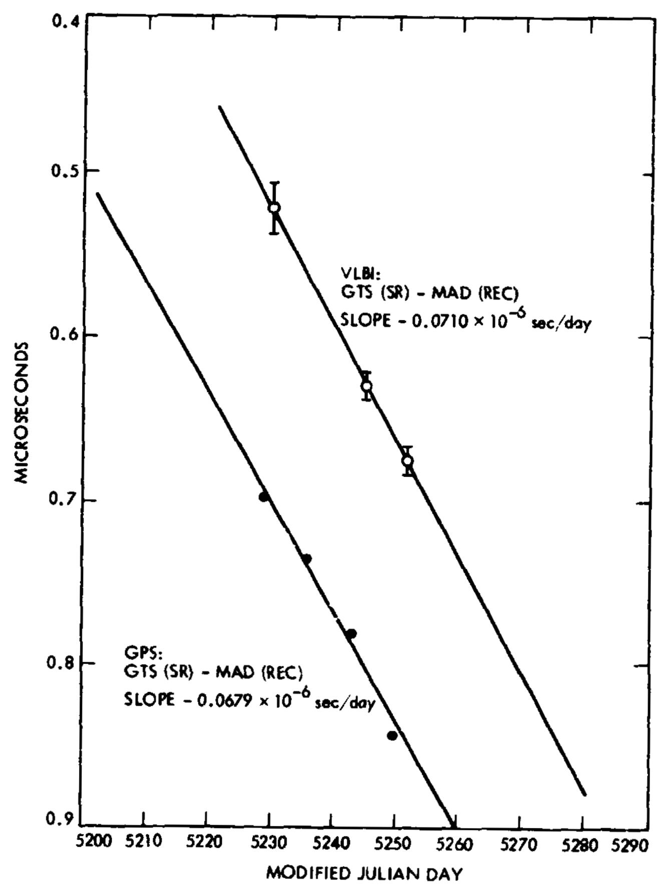

Fig. 6. Comparison of GPS and VLBI clock offset measurements: Goldstone–Madrid